Available online at www.sciencedirect.com
SciVerse ScienceDirect
Procedia Engineering 47 (2012) 1013 – 1016
Procedia Engineering
www.elsevier.com/locate/procedia
ELSEVIER

Proc. Eurosensors XXVI, September 9-12, 2012, Kraków, Poland

Use of electromechanical feedback in MEMS for suppressing electronics noise

Panu Helistö *, Hannu Sipola, Heikki Seppä

VTT Technical Research Centre of Finland, PO Box 1000, 02044 VTT, Finland

Abstract

At the pull-in point, a capacitive MEMS sensor becomes infinitely sensitive to applied force as the effective spring constant goes to zero because of electromechanical feedback We show that this phenomenon can be used to fully eliminate the noise contribution of readout electronics. Experimentally, we show that the electronics noise and interference contribution to system resolution could be suppressed by an order of magnitude, reaching the intrinsic resolution of the MEMS microphone. Experiments are in good agreement with a theory based on a small signal model of a harmonic MEMS oscillator. The technique allows the use of standard integrated electronics with noise-critical MEMS sensors, such as microphones, pressure sensors and accelerometers.

Keywords: MEMS sensor, readout noise, pull-in

1. Introduction

A capacitive MEMS sensor and standard integrated readout electronics are difficult to match to each other because of the high impedance of the former and the small or medium optimum source impedance of the latter. In addition, CMOS circuits have typically a large 1/f noise contribution. Thus, instead of the mechanical noise of the MEMS sensors, the dominant noise mechanism of the sensor-readout system can as well be electronics noise. To avoid the impedance mismatch and the 1/f noise of the readout a good solution is to use RF readout techniques, typically a capacitance bridge (see e.g. [1]). Even with RF readout, readout noise remains finite. We present here a method that can fully eliminate the noise of the readout electronics. The method utilizes positive electromechanical feedback near the pull-in point.

Nomenclature

C_0	Capacitance of the MEMS sensor with F_{ext} but without bias voltage
D_0	Gap between the MEMS plates with F_{ext} but without bias voltage
δF_{ext}	Force excitation
$\delta F_{n,MEMS}$	RMS value of the mechanical noise of the microphone
F_{ext}	Static external force

* Corresponding author. Tel.: +358-40-5783577, *E-mail address*: panu.helisto@vtt.fi.

doi:10.1016/j.proeng.2012.09.319

k	Spring constant
m	Mass of moving membrane
δV	Signal voltage
V	Applied static voltage
V_{RF}	Applied rms RF voltage
V_b	$(V^2 + V_{\mathrm{RF2}})^{1/2}$ – bias voltage
$V_{b,co}$	Crossover voltage at which mechanical and electrical noise contributions are equal
V_{pullin}	Pull-in voltage
δX	Membrane displacement due to δF_{ext}
$\delta X_{n,RF}$	RMS value of the displacement noise of the RF bridge due to electronics noise
X	Static membrane displacement due to V_b

2. Model

2.1. Setup

The setup is described in Fig. 1. The capacitance of a MEMS sensor is monitored with an RF capacitance bridge, the output of which is downmixed, amplified and fed back to the MEMS membrane. The reference capacitor C_{REF} and DC voltage V are adjusted so that the sensor is near the pull-in point. The voltage δV is the signal voltage induced by a small force excitation δF_{ext}. The physical signal to be sensed is the force on the MEMS membrane but it can as well be pressure, acceleration etc. In effect, electrical feedback makes the system displacement biased instead of voltage biased as electrical feedback tends to maintain the MEMS capacitance constant. Like charge bias and contrary to voltage bias, displacement bias is always stable. In [2] another technique to operate above pull-in was demonstrated utilizing charge controlled readout and electrical feedback.

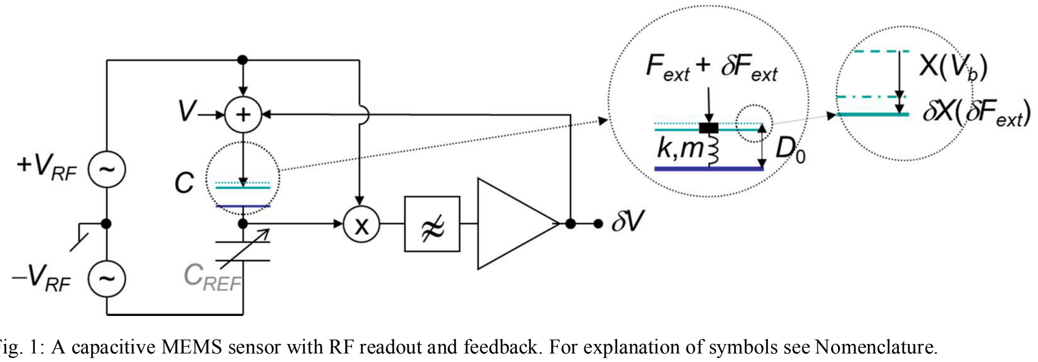


Fig. 1: A capacitive MEMS sensor with RF readout and feedback. For explanation of symbols see Nomenclature.

The displacement - voltage curve of such a system is shown in Fig 2a. The bias voltage causes an electromechanical force that pulls the MEMS plates towards each other. As the voltage is increased, the well-known pull-in ultimately takes place and the system spontaneously collapses. At pull-in, a finite displacement fluctuation δX is mapped to a negligible voltage fluctuation $\delta V \approx 0$. This is described at DC by the equation [3]

$$\delta V = k' D^2/(V C_0 D_0)\ \delta X, \tag{1}$$

where

$$k' = k - C_0 D_0 V_b^{\,2}/D^3 = k\,(1\text{-}3X/D_0)/(1\text{-}X/D_0) \tag{2}$$

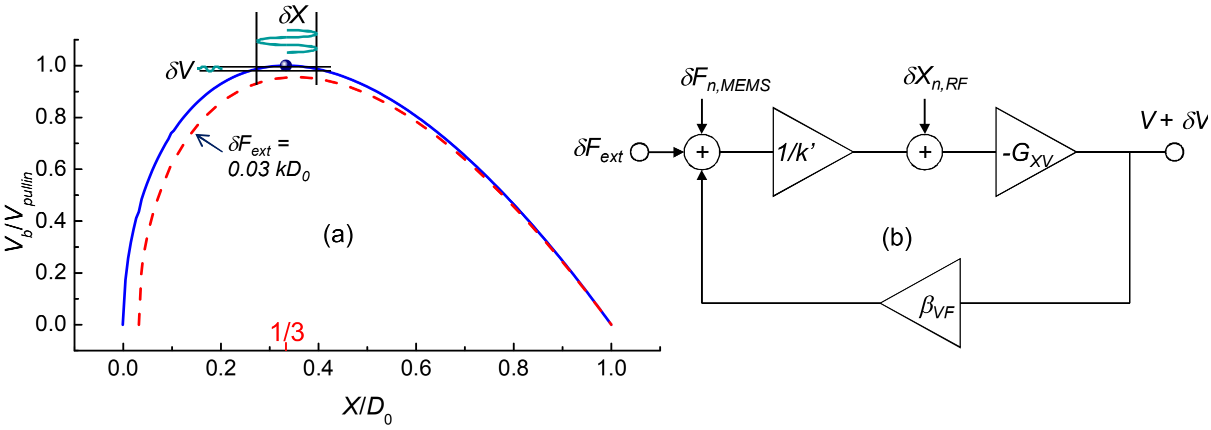


Fig. 2: (a) Displacement – voltage curve of a MEMS capacitor. At pull-in ($X = D_0/3$), a finite displacement fluctuation δX is mapped to a negligible voltage fluctuation δV. An applied force scales the $X – V$ curve. (b) Feedback loop description of the system in Fig. 1.

is an effective spring constant. At pull-in $k' = 0$ and above pull-in k' is negative. In addition, the effect of a sma applied force is shown in Fig 2a to demonstrate the nonzero force-to-voltage responsitivity at pull-in. For details of tl derivation of Eqs. (1) and (2) and for calculation of the AC behaviour of the system see [3].

2.2. Small signal model

The system behaviour can be illustrated with the small signal feedback loop of Fig. 2b. The two main noise sourc are reduced here to 1) an equivalent thermal force noise of the MEMS sensor and 2) an equivalent displacement noi of the RF bridge, caused by the noise of the readout electronics. Our target is to reduce the latter contribution so th the resolution is dominated by the sensor, not by the readout. $1/k'$ can be considered as the mechanical gain from for to displacement, $G_{XV} \propto V_{RF}/D_0$ is the displacement-to-voltage gain of the bridge and $\beta_{VF} = VC_0D_0/D^2$ is tl electromechanical feedback coefficient of the system. As feedback does not affect noise properties, it is evident that b increasing $1/k'$, i.e., by approaching the pull-in point, the relative contribution of the electronics to system resolution reduced. Sufficiently near the pull-in point, the noise contribution of an arbitrary capacitance bridge can thus l eliminated! The crossover point of equal MEMS and electronics noise contribution is determined by

$$k'(V_{b,co}) = \delta F_{n,MEMS}/\delta X_{n,RF} \tag{3}$$

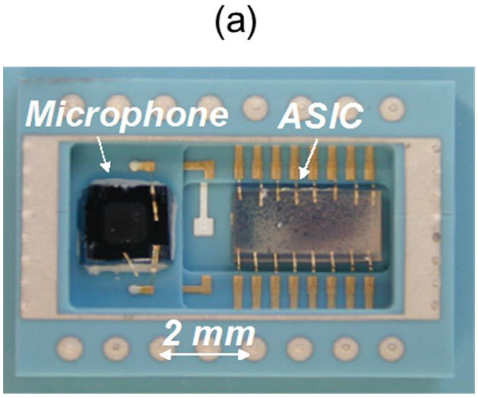
where $V_{b,co}$ is the bias voltage corresponding to crossover. Dissipation and inertia of the MEMS device limit the usab frequency range [3].

3. Experimental and conclusions

An experimental MEMS microphone with low-tensile stress polysilicon membrane [4] and an integrat capacitance bridge circuit designed inhouse and fabricated with 0.6-µm CMOS process of Austriamicrosysten through Europractice [5] were used to test the readout principle (Fig. 3a).

Based on the microphone parameters, we obtain $F_{n,MEMS}/A_{eff} \approx 6.5$ µPa/Hz$^{1/2}$ as the intrinsic resolution of the MEN microphone when $V_b = 0.921V_{pullin}$. Here $A_{eff} \approx 0.92$ mm^2 is the effective moving area of the membrane. The pull- voltage of the microphone is 5.68 V giving $k \approx 147$ N/m and the displacement resolution of the AC bridge w measured to be $\delta X_{n,RF} \approx 0.12$ pm/Hz$^{1/2}$. For other experimental details, see [3]. Solving Eq (3) with the calculat microphone parameters and measured displacement resolution of the bridge, we get $V_{b,co} \approx 0.97V_{pullin}$ as the crossov voltage.

In Fig 3b, measured pressure noise spectra are shown at different bias settings when going through the pull-in poir Note that the microphone can be operated also above the pull-in point (curve 0.999>). With the lowest bias voltag $0.921V_{pullin}$, the resolution is 11 µPa/Hz$^{1/2}$. At $0.984V_{pullin}$ the noise level is between 7 and 8 µPa/Hz$^{1/2}$ excluding tl electromagnetic interference peaks, and with the higher bias settings the noise saturates to 6 – 6.5 µPa/Hz$^{1/2}$ predicted by the model.



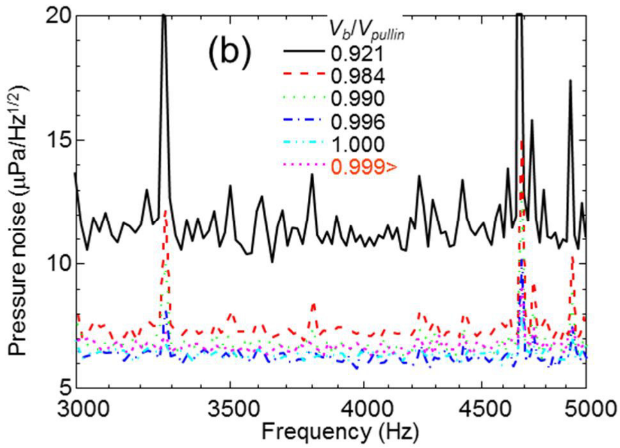


Fig. 3(a) A photograph of the MEMS microphone and readout circuit. (b) Noise spectra of the system at different values of V_b/V_{pullin}. Curve 0.999> is obtained above the pull-in point.

A remarkable effect is the suppression of the amplitude of the interference peaks, caused by nearby measurement instruments an 50-Hz power lines. Typically an order of magnitude suppression was observed when approaching the pull-in (see e.g. the peaks at 3.3 kHz and 4.7 kHz in Fig. 3b). The results are quantitatively explained by the model assuming that EMI enters into the feedback loop after downmixing of the RF signal. This is plausible because of the low signal level after the mixer.

In conclusion, we have demonstrated an efficient method to eliminate electronics noise and interference when reading out the signal of a capacitive MEMS sensor. The technique is based on driving the MEMS device close to pull-in. Capacitance bias realised with an RF bridge readout and electrical feedback ensures system stability. The method allows the use of standard, low cost CMOS electronics even in demanding MEMS sensing applications.

Acknowledgements

We thank Drs Altti Torkkeli, Mari Laamanen and Hannu Kattelus for fabricating the MEMS microphone. Financial support from TEKES and the Academy of Finlad (Centre of Excellence program) is acknowledged.

References

[1] Wu J, Fedder GK, Carley IR. A low-noise low-offset capacitive sensing amplifier for a 50-µg/Hz$^{1/2}$ monolithic CMOS MEMS accelerometer, *IEEE Journal of Solid-State Circuits* 2004;**39**:722-730.

[2] Langfelder G et al. Readout of MEMS capacitive sensors beyond the condition of pull-in instability. *Sensors and Actuators A* 2011;**167**: 374 – 384.

[3] Helistö P, Sipola H, Seppä H. Noise suppression of MEMS readout near pull-in. *Sensors & Actuators A*, in press.

[4] M. Ylonen, A. Torkkeli, H. Kattelus, In situ boron-doped LPCVD polysilicon with low tensile stress for MEMS applications, *Sensors and Actuators A* 2003;**109**:79-87.

[5] http://www.europractice-ic.com/.